Microencapsulated Phase Change Materials for Energy Efficient Buildings

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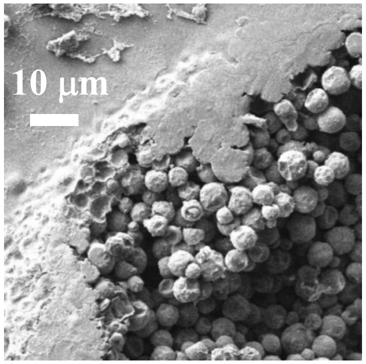
A New Kind of Composite Phase Change Envelope for ZNE Buildings

- Objectives
  - Reduce and shift electricity demand to off-peak times
  - Reduce utilities capital investment
  - Contribute to zero net energy buildings
- Strategy
  - Use microencapsulated phase change materials (PCM)
    - Increase thermal mass of buildings
    - Absorb heat during the day and release it at night



- Engineering needs
  - Material processing
    - avoid capsule aggregation, flotation, breakage, durability
  - Predict and measure thermomechanical properties of PCM-mortar composites
  - Predict thermal response of the PCM-mortar composite building envelope
  - Estimate energy and cost savings in buildings
  - Develop design tools and design rules for deployment

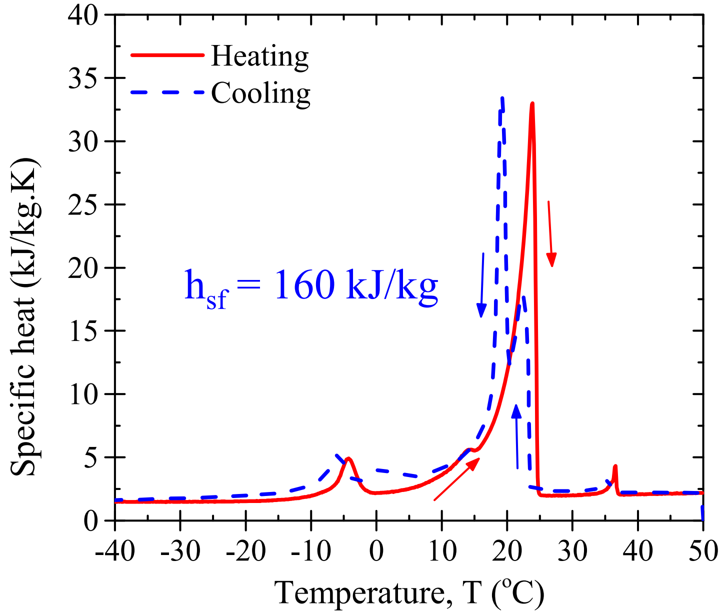
- Predict and measure thermomechanical properties of PCM composites

Effective specific heat of PCM microcapsules and composites
Effective thermal conductivity
Effective compressive strength
Effective Young's modulus
Effective thermal deformation coefficient

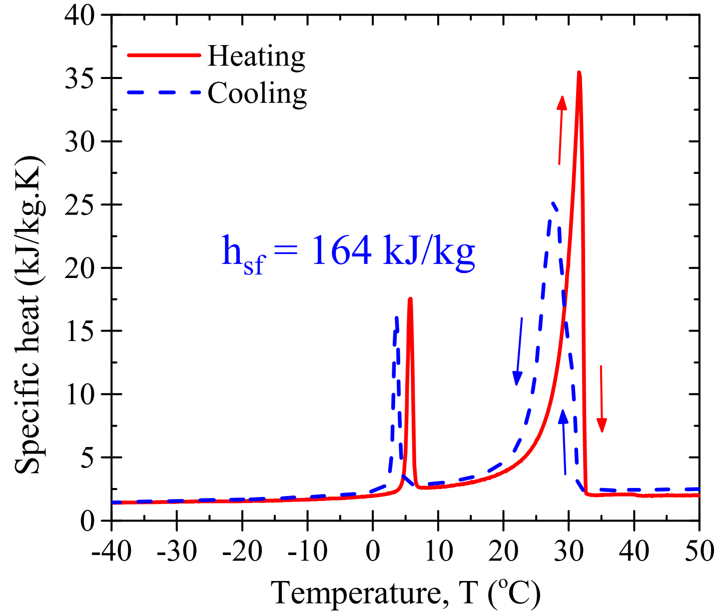
Specific heat of PCM

- Microencapsulated PCM specific heat
  - Measured via DSC (scan rate: 1°C/min)

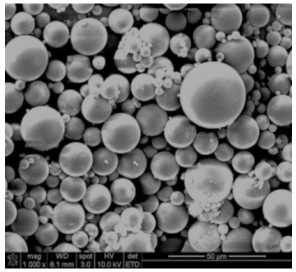
Microtek-MPCM24D



Microtek-MPCM32D



- Observations
  - Multiple peaks due to multicomponent PCMs
  - Area under the curve is the latent heat of fusion
  - Slight difference if the sample is heated or cooled



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PCM Database

- A database of over 500 PCMs, including over 250 commercially available PCMs, was compiled
  - Available via our lab webpage as an Excel file: http://seas.ucla.edu/~pilon/downloads.htm#section4
  - Also added to the Wikipedia article on phase change materials: https://en.wikipedia.org/wiki/Phase-change_material

Commercially available PCMs near room temperature [edit]

Material	Supplier	Type	Form	Melting temperature, T_m °C	Melting temperature, T_m °F	Enthalpy ΔH kJ/kg	Solid Density, ρ kg/m³	Liquid Density, ρ kg/m³	Solid Thermal conductivity, k W/m·K	Liquid Thermal conductivity, k W/m·K	Solid Specific heat, c_p kJ/kg·K	Liquid Specific heat, c_p kJ/kg·K
18 C° Infinite R Energy Sheet	Insolcorp[39]	Inorganic	Macro-encapsulated	18	64.4	200	1540		0.54	1.09		3.14
21 C° Infinite R Energy Sheet	Insolcorp[39]	Inorganic	Macro-encapsulated	21	69.8	200	1540		0.54	1.09		3.14
23 C° Infinite R Energy Sheet	Insolcorp[39]	Inorganic	Macro-encapsulated	23	73.4	200	1540		0.54	1.09		3.14
25 C° Infinite R Energy Sheet	Insolcorp[39]	Inorganic	Macro-encapsulated	25	77	200	1540		0.54	1.09		3.14
29 C° Infinite R Energy Sheet	Insolcorp[39]	Inorganic	Macro-encapsulated	29	84.2	200	1540		0.54	1.09		3.14
savE[40] HS 33N[41]	Pluss[42]	Inorganic	Bulk	-30	-22	224	1425					

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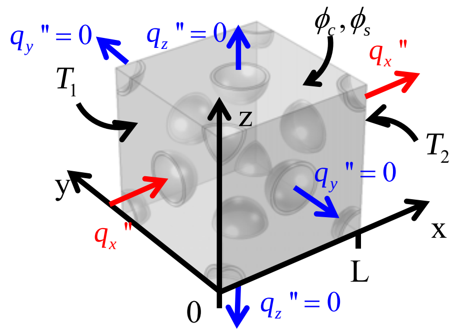
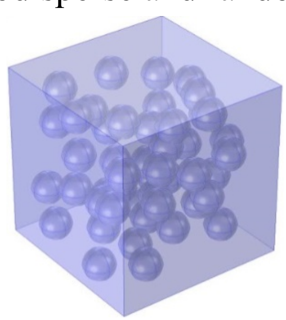
Effective Thermal Conductivity: Simulations

- PCM-cement composites

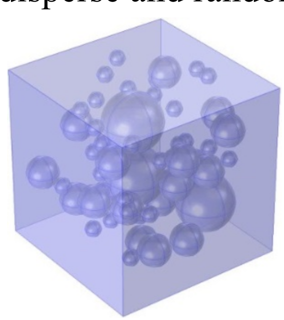
Monodisperse and ordered



Monodisperse and randomly distributed



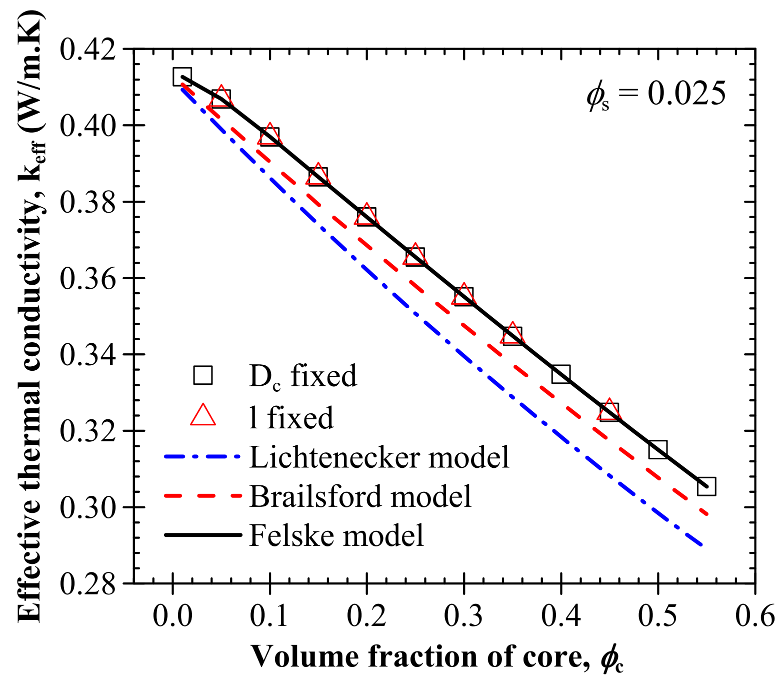
Polydisperse and randomly distributed



- Felske model*

$$k_{eff} = \frac{k_m\left(1-\phi_c-\phi_s\right)\left[6+4\frac{\phi_s}{\phi_c}+2\frac{\phi_s k_c}{\phi_c k_s}\right]+\left(1+2\phi_c+2\phi_s\right)\left[\left(3+\frac{\phi_s}{\phi_c}\right)k_c+2\frac{\phi_s}{\phi_c}k_s\right]}{\left(2+\phi_c+\phi_s\right)\left[3+2\frac{\phi_s}{\phi_c}+\frac{\phi_s k_c}{\phi_c k_s}\right]+\left(1-\phi_c-\phi_s\right)\left[\left(3+\frac{\phi_s}{\phi_c}\right)\frac{k_c}{k_m}+2\frac{\phi_s k_s}{\phi_c k_m}\right]}$$

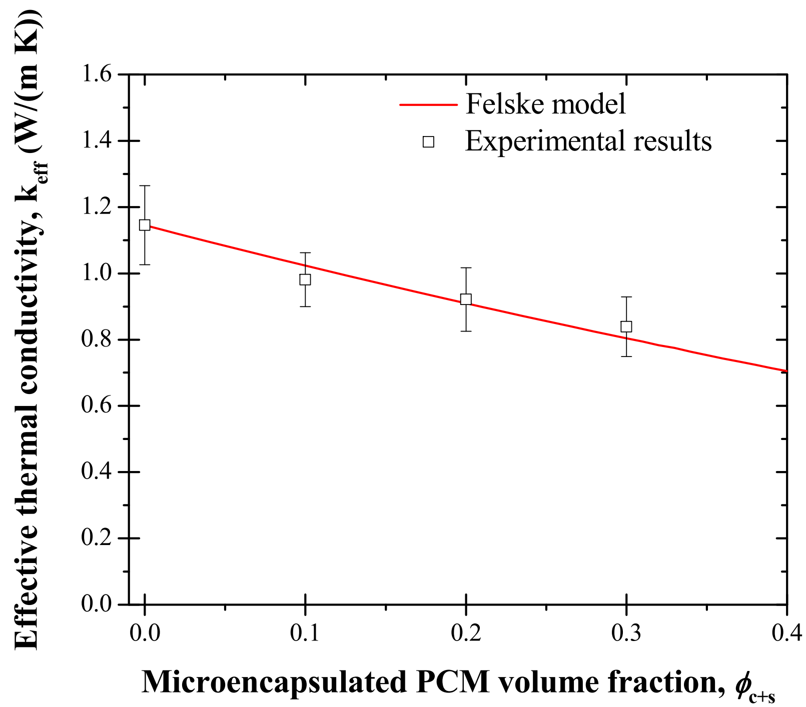
- Results



*Felske, J.D., *Int. J. Heat Mass Transfer*, 47, 3453-3461, 2004.

Effective Thermal conductivity: Experiments

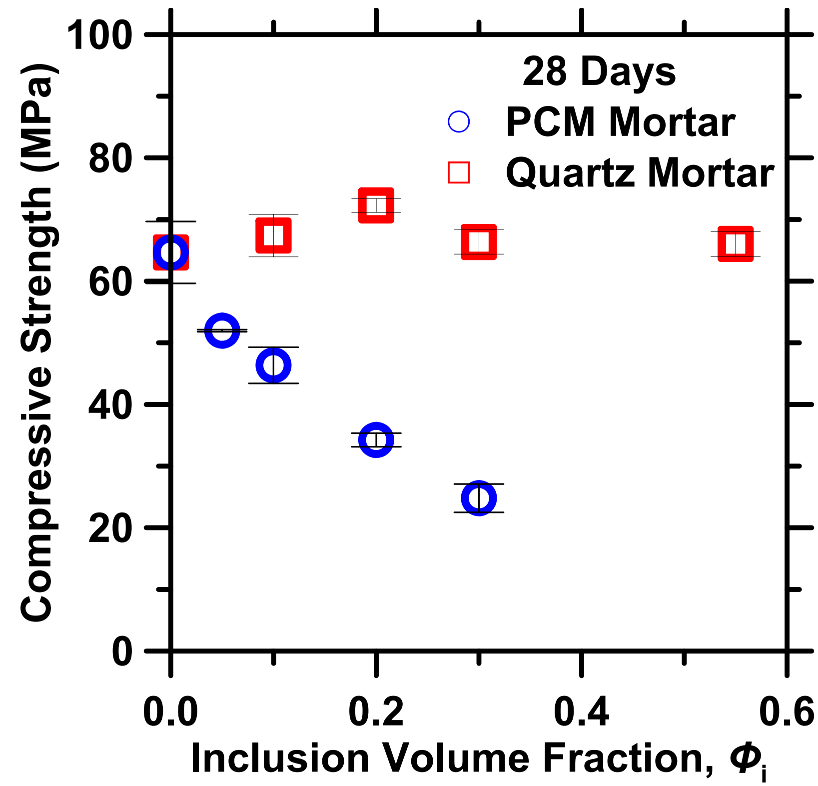
- Sample composition
  - Cement type
    - Ordinary Portland cement type I
  - Water/cement ratio
    - 0.45
  - Microencapsulated PCM (MPCM24D)
    - T_{pc} = 24°C
    - 17-20 μm in diameter
    - Volume fraction ϕ_{c+s}: 0 to 30%
  - Quartz grains (optional)
    - 150-600 μm in diameter
    - Added such that $\phi_{c+s} + \phi_q$ = 55%
  - Aging
    - aged in humid air for 24 hours
    - aging in air for 28 days



- Observations
  - k_{eff} was independent of T
  - Adding MPCM reduced k_{eff}
  - Excellent agreement with Felske model

Effective Compressive strength: Experiments

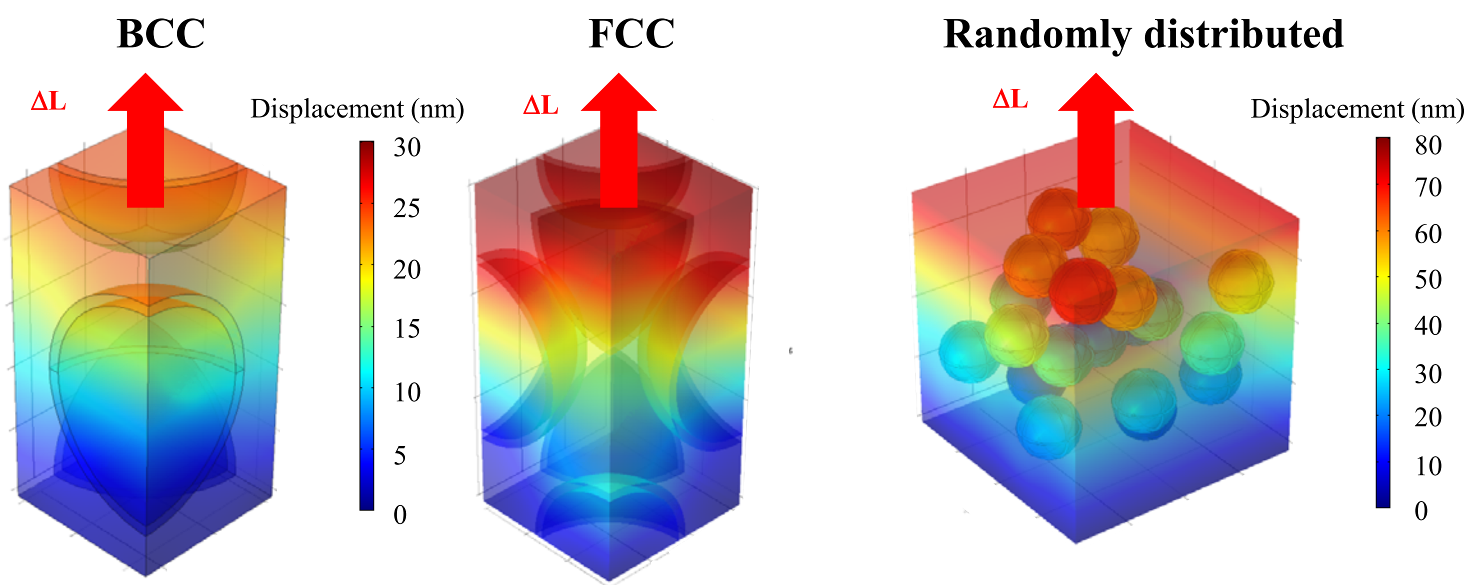
- Observations
  - Strength depends on "weakest link"
    - PCMs inclusions
      - reduce strength
      - Weaker than cement paste
    - Quartz inclusions
      - do not increase strength
      - Cement paste weakest link
- Limits how much PCM can be added to concrete
  - With 20% PCM, still above 30 MPa
    - Minimum strength specified by ACI 318 for structural concrete*



*American Concrete Institute, *Building code requirements for structural concrete*, 2008, Farmington Hills, MI, USA.

Effective elastic moduli: Simulations

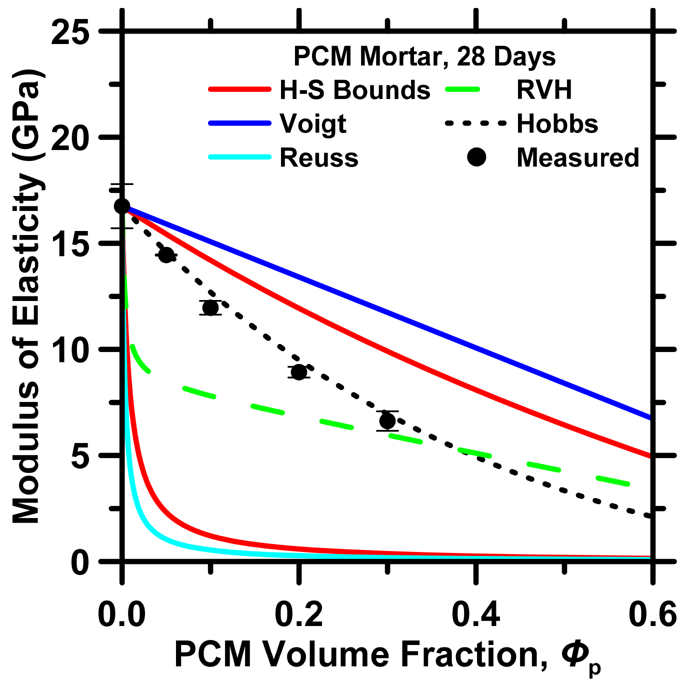
- Numerical simulations of elastic deformation

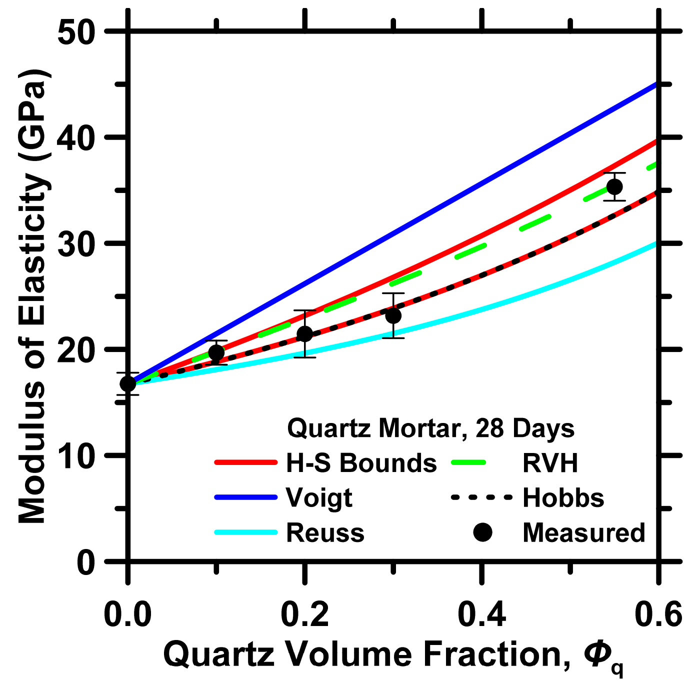


- Conclusions
  - Effective Young modulus were identical for
    - BCC and FCC packing of monodisperse microcapsules
    - Randomly distributed polydisperse microcapsules
  - Identified effective medium approximations for the effective moduli
    - Hobbs model (1971) for $E_m \sim E_s \sim E_c$
    - Garboczi and Berryman model (2001) for $E_m < E_c$

Effective Mechanical Properties: Experiments

- Experimental results





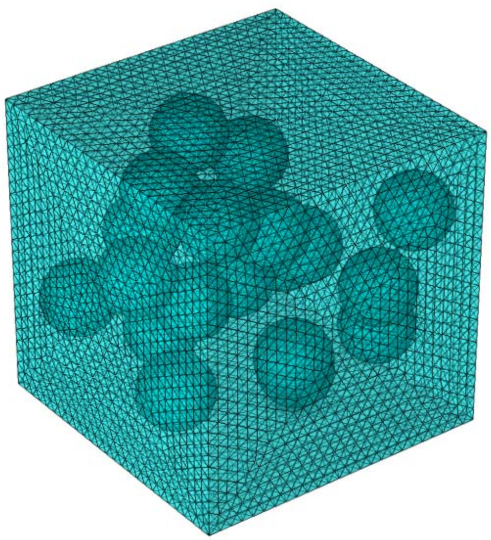
- Conclusions
  - Adding PCM degrade the elastic moduli and compressive strength
  - One can compensate by adding stiff quartz (or sand) inclusions
  - Hobbs model agree well with experimental data

*Hobbs, D.W., *Materiaux et Construction,* **4**, 107-114, 1971.

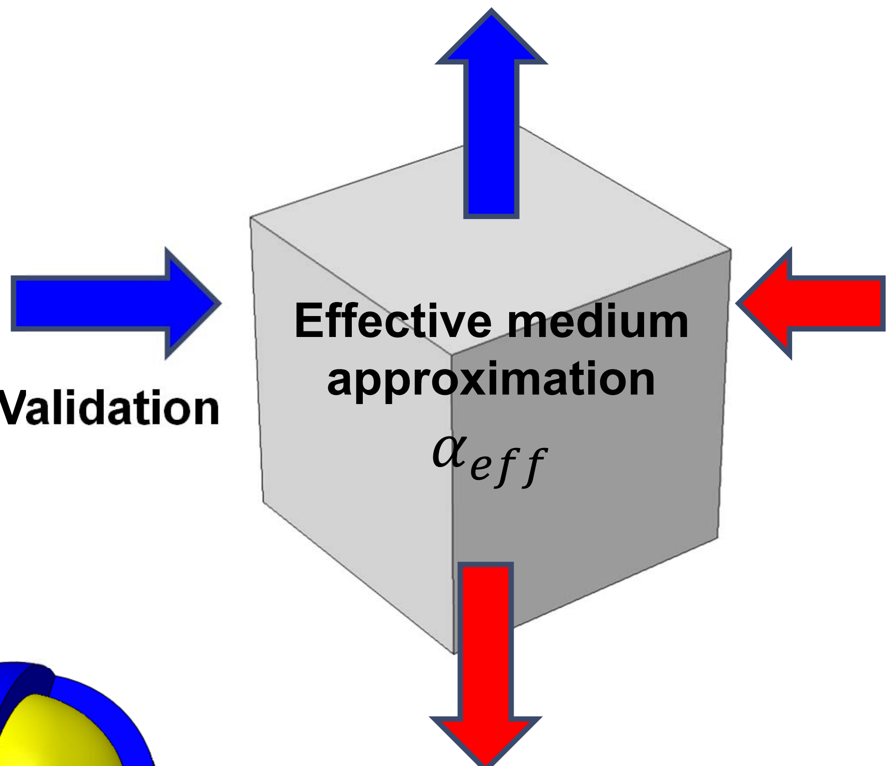
Effective Thermal Deformation Coefficient

Composite thermal deformation coefficient

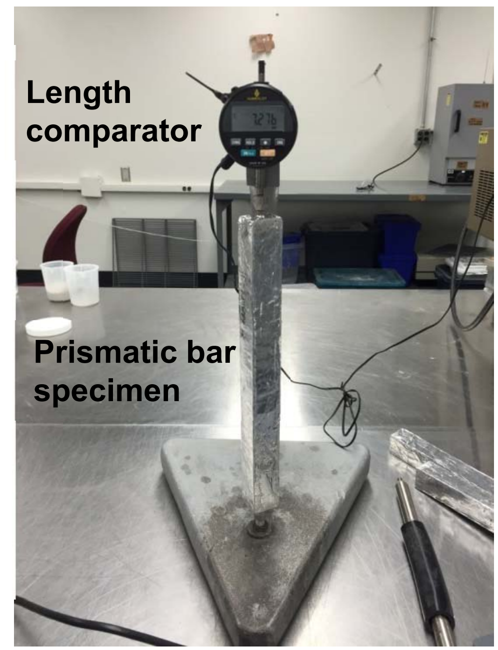
Finite element simulations

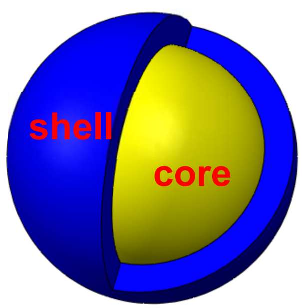


Validation



Experimental measurements



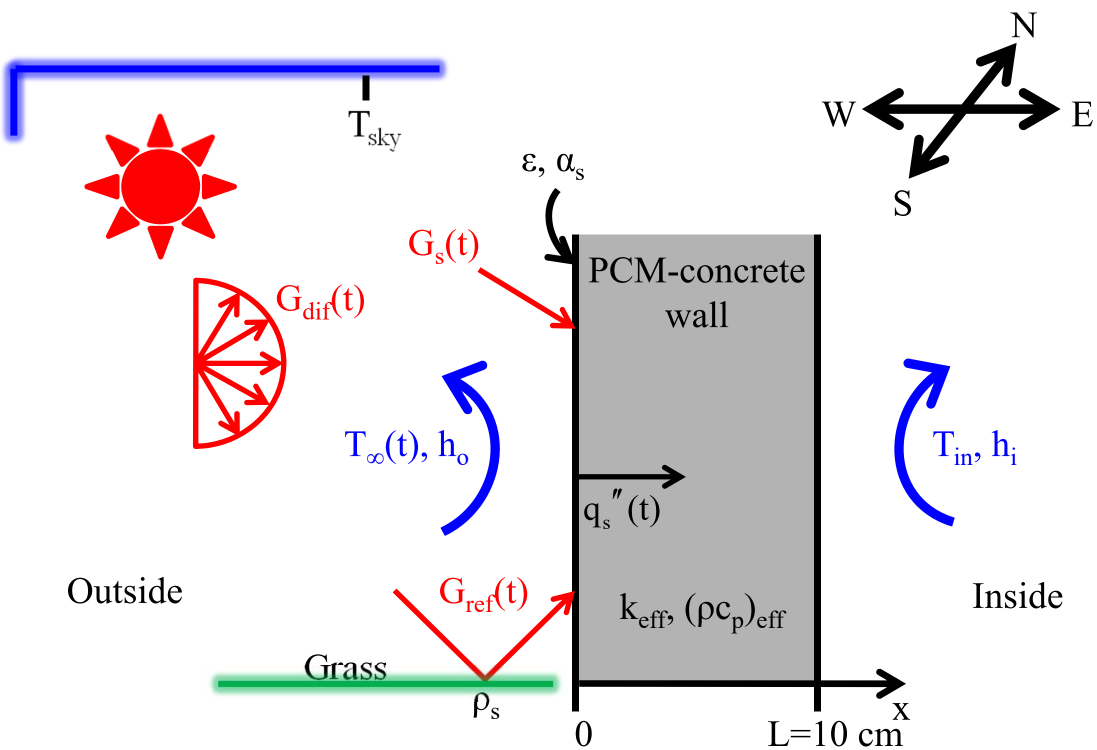


Inclusion thermal deformation coefficient

- Predict thermal response of the PCM-mortar composite building envelope
- Estimate energy and cost savings in buildings

Design and Optimization of PCM-composite building envelope

- Typical one story single-family home
  - Average floor area in Western U.S. in 2013: 2534 ft^2 (241.5 m^2)*
  - Exterior wall surface areas were obtained from HEED software
    - Heat transfer through glazing and roof surfaces was not considered

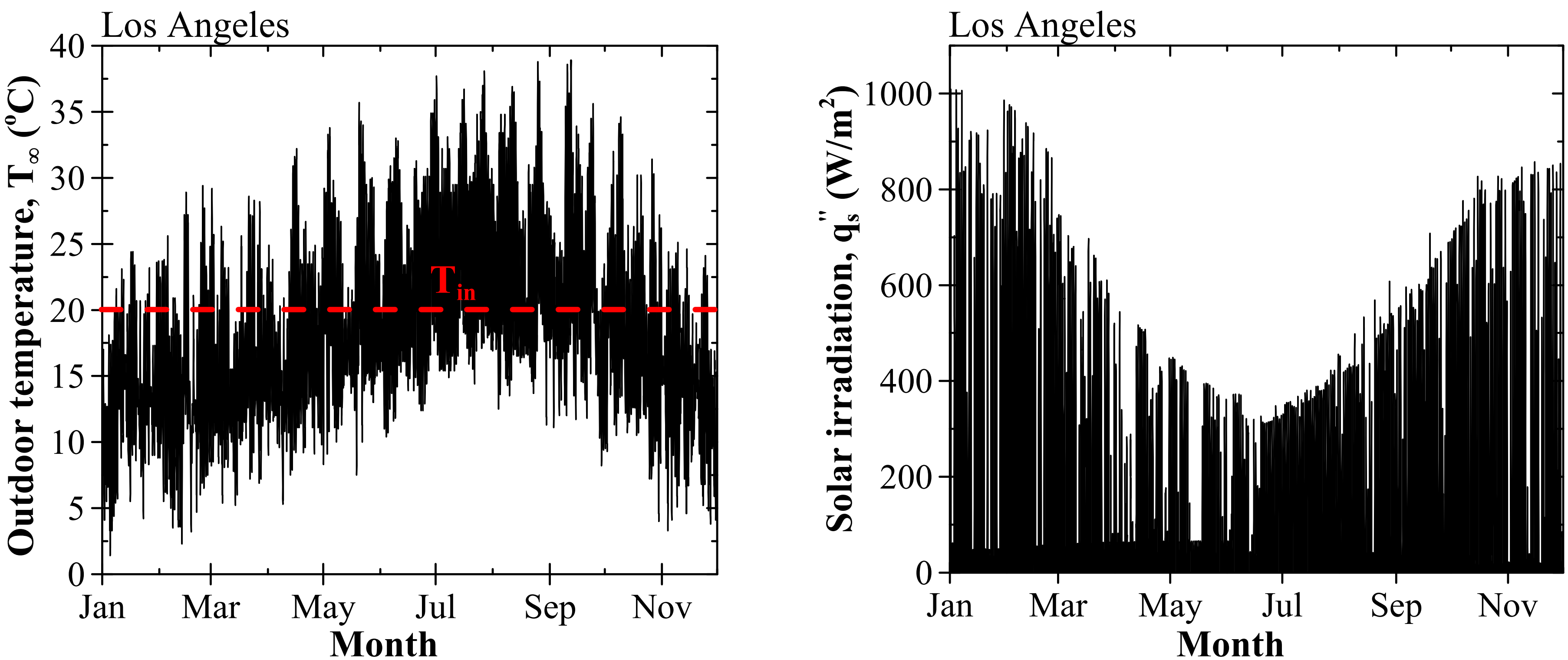


Wall orientation	Wall area	
	ft^2	m^2
East	300	27.9
West	300	27.9
North	424	39.4
South	404	37.5

* https://www.census.gov/construction/chars/highlights.html

Annual weather conditions

- Outdoor temperature and solar irradiation in Los Angeles



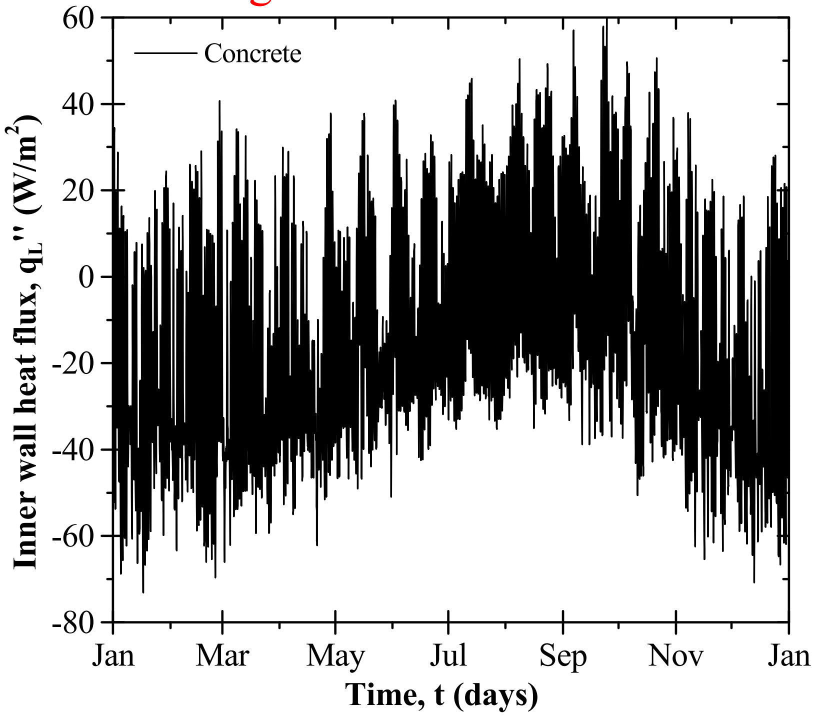
- Similar simulations for San Francisco

Effect of ϕ_c - South Wall

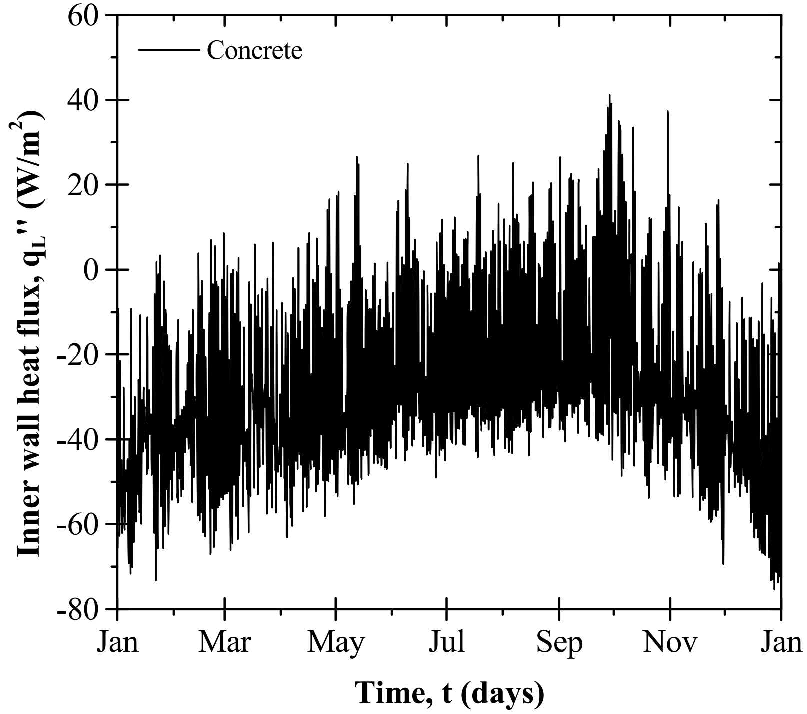
- Parameters

  $T_{in} = 20^{\circ}C$, $\phi_c = 0$ (concrete)

Los Angeles



San Francisco



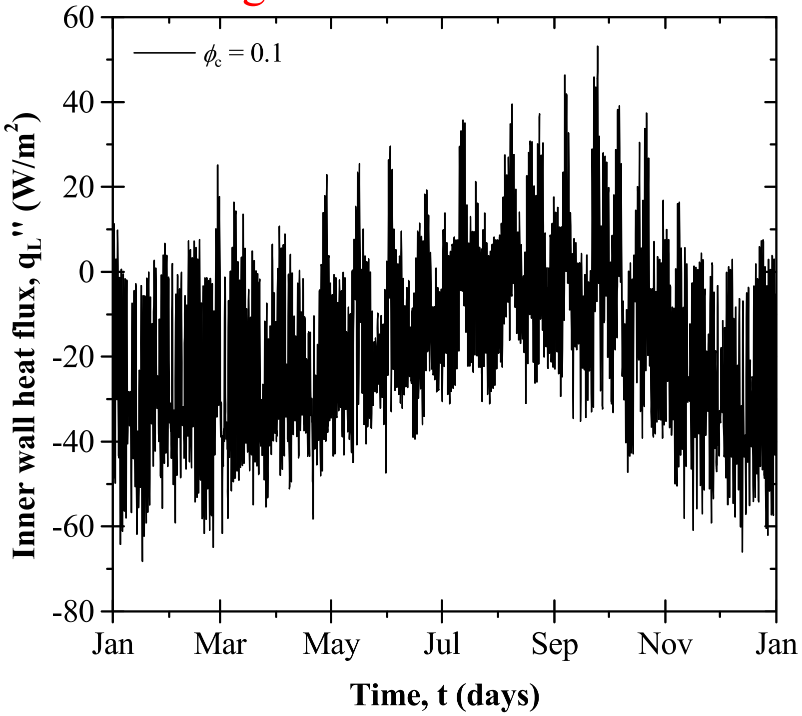
A.M. Thiele et al., 2015. Energy Conversion and Management, **103**, 374-386.

Effect of ϕ_c - South Wall

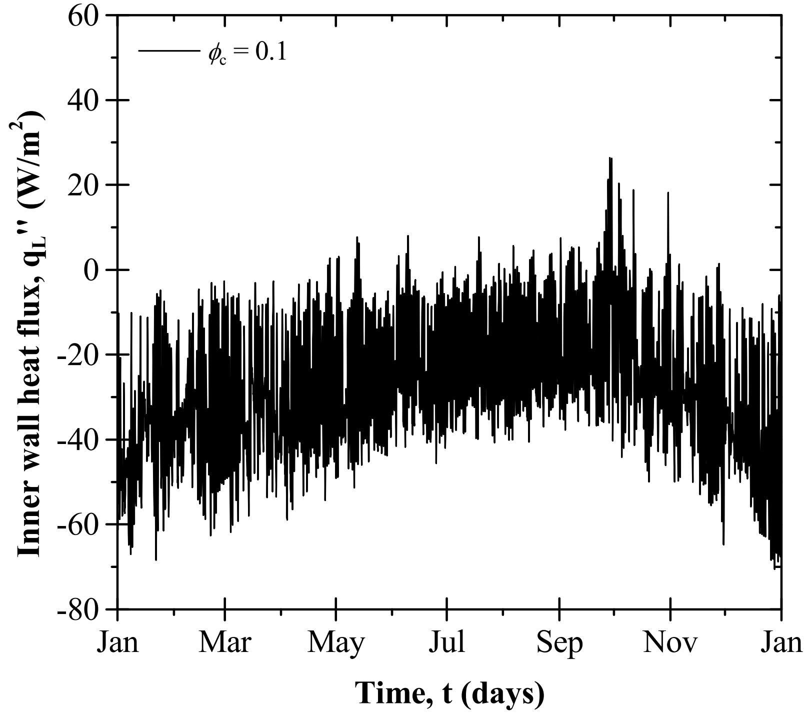
- Parameters

$$T_{pc} = T_{in} = 20^\circ C,\ \Delta T_{pc} = 3^\circ C,\ h_{sf} = 180\ kJ/kg,\ \phi_c = 0.1,\ \phi_s = 0.08$$

Los Angeles



San Francisco

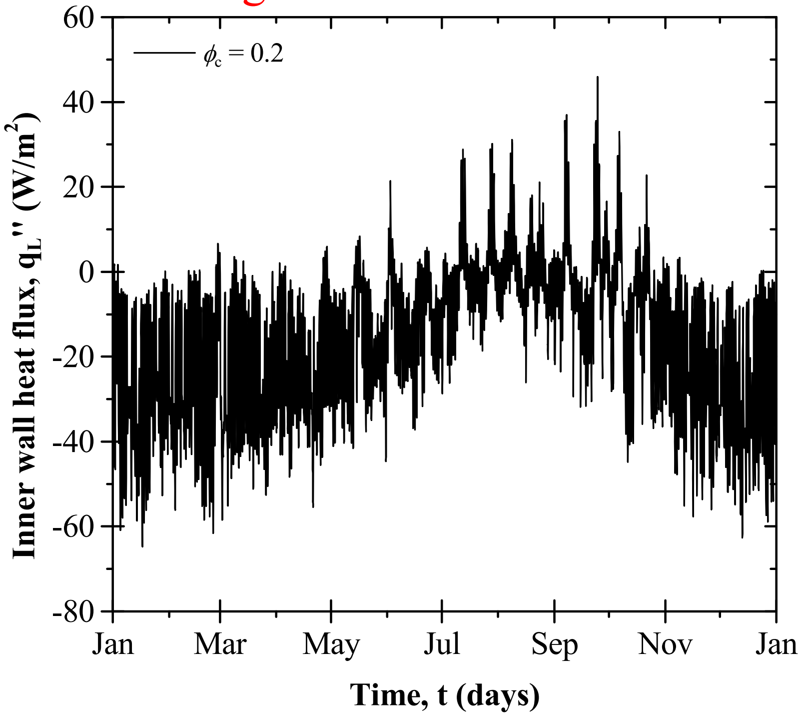


Effect of ϕ_c - South Wall

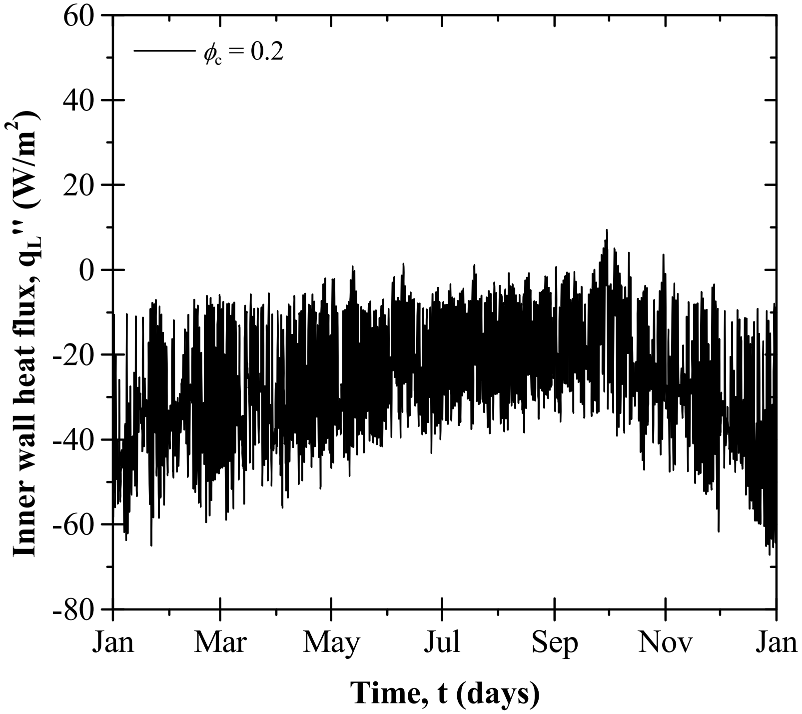
- Parameters

$$T_{pc} = T_{in} = 20^{\circ}C,\ \Delta T_{pc} = 3^{\circ}C,\ h_{sf} = 180\ kJ/kg,\ \phi_c = 0.2,\ \phi_s = 0.08$$

Los Angeles



San Francisco

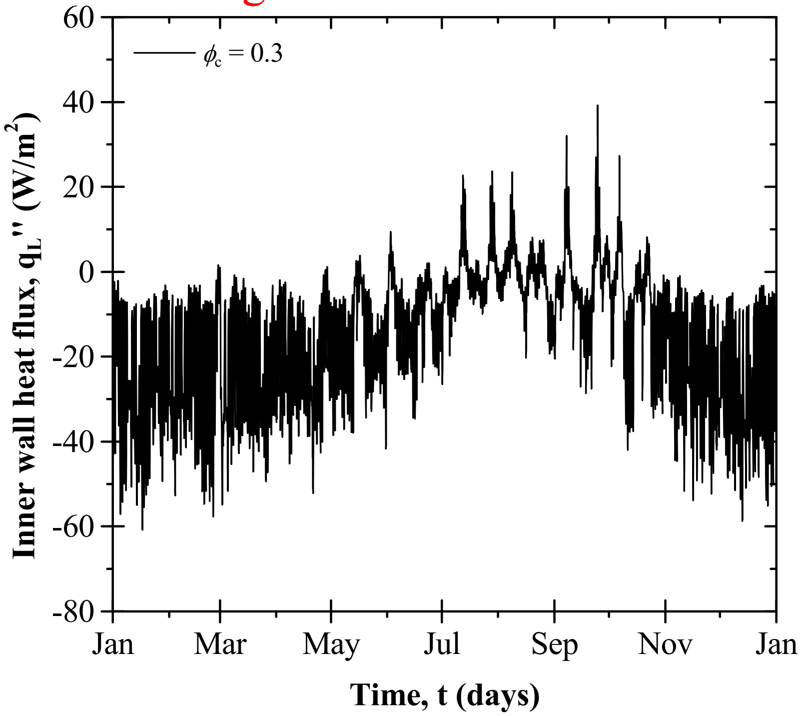


Effect of ϕ_c - South Wall

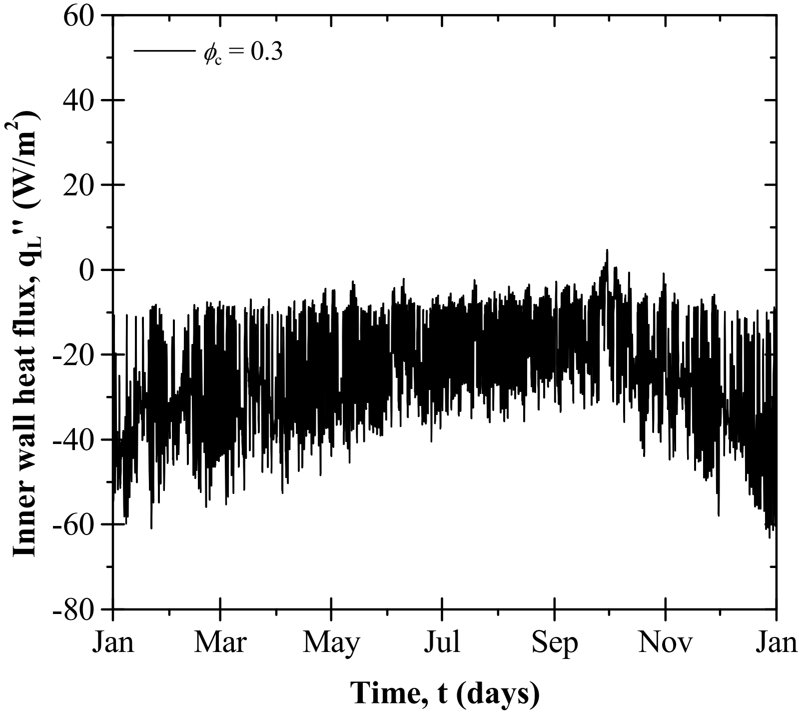
- Parameters

$$T_{pc} = T_{in} = 20^\circ C,\ \Delta T_{pc} = 3^\circ C,\ h_{sf} = 180\ kJ/kg,\ \phi_c = 0.3,\ \phi_s = 0.08$$

Los Angeles



San Francisco



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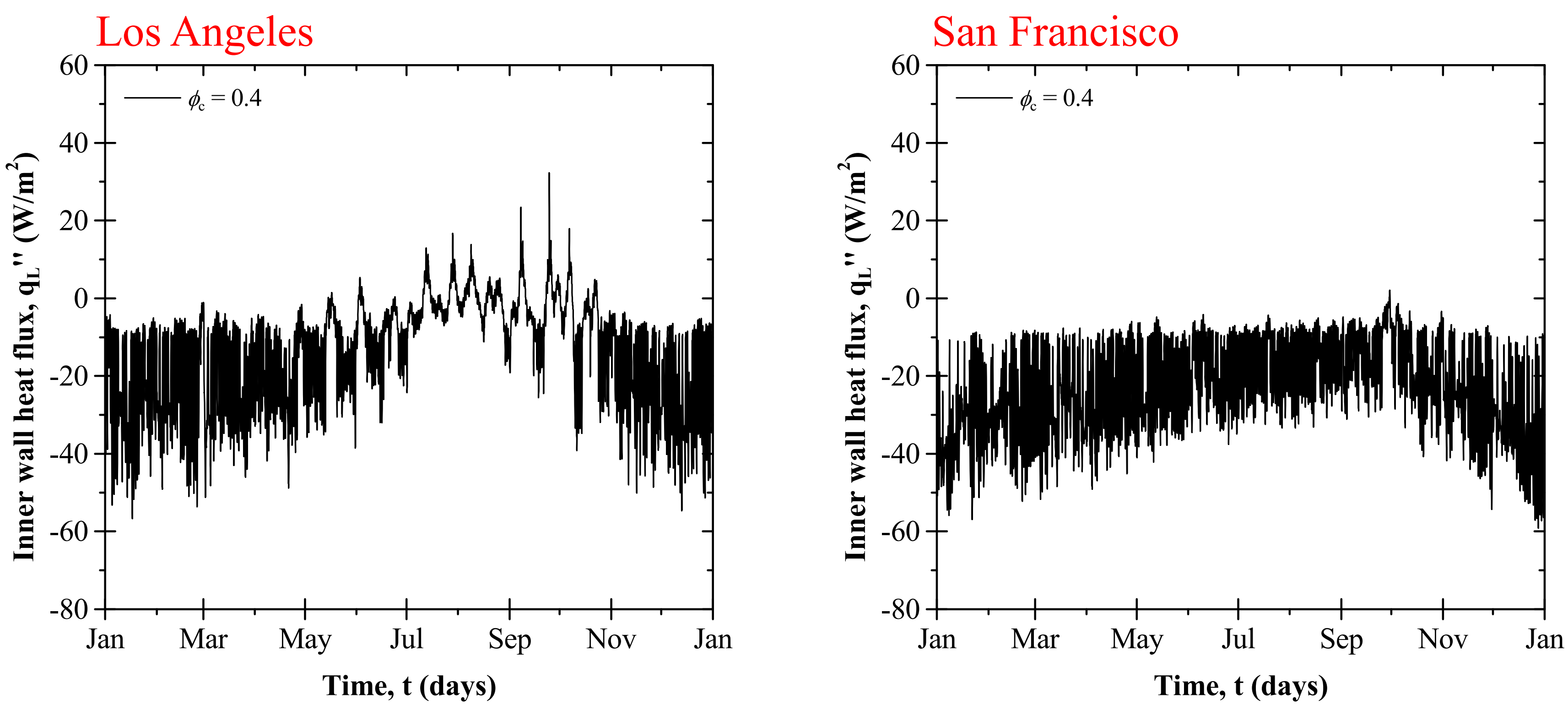
Effect of ϕ_c - South Wall

- Parameters

$$T_{pc} = T_{in} = 20^\circ C,\ \Delta T_{pc} = 3^\circ C,\ h_{sf} = 180\ kJ/kg,\ \phi_c = 0.4,\ \phi_s = 0.08$$



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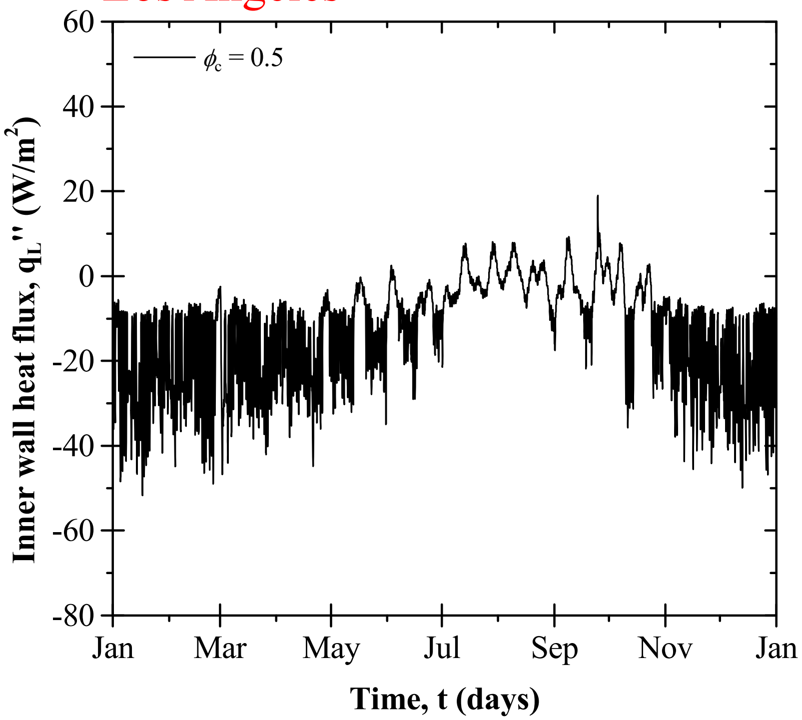
Effect of ϕ_c - South Wall

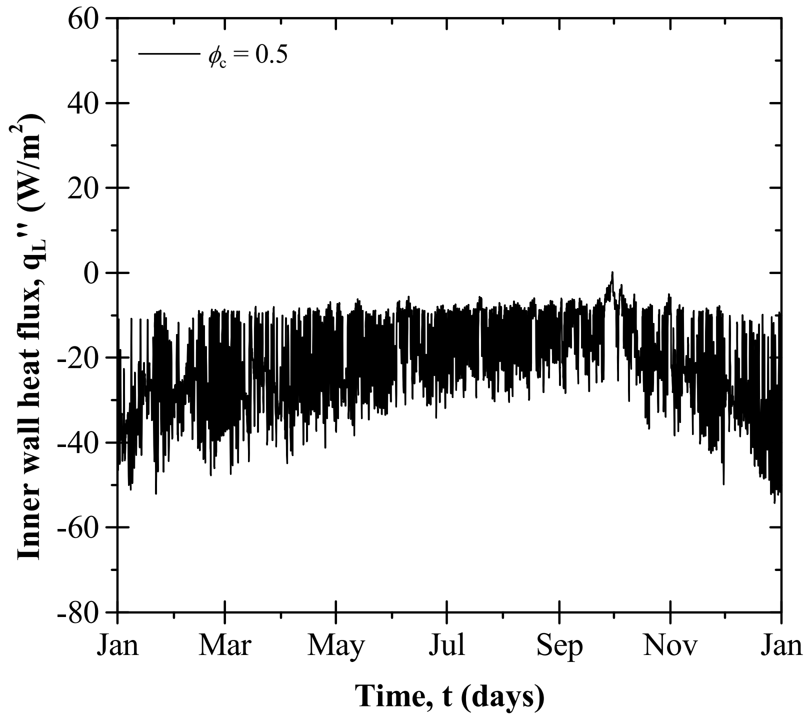
- Parameters

$$T_{pc} = T_{in} = 20^{\circ}C,\ \Delta T_{pc} = 3^{\circ}C,\ h_{sf} = 180\ kJ/kg,\ \phi_c = 0.5,\ \phi_s = 0.08$$

Los Angeles



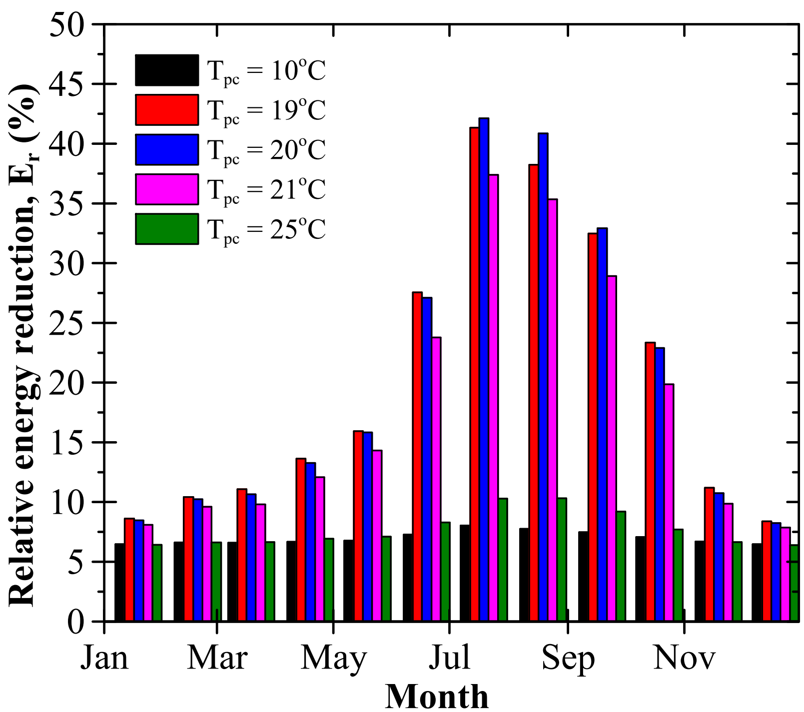
San Francisco

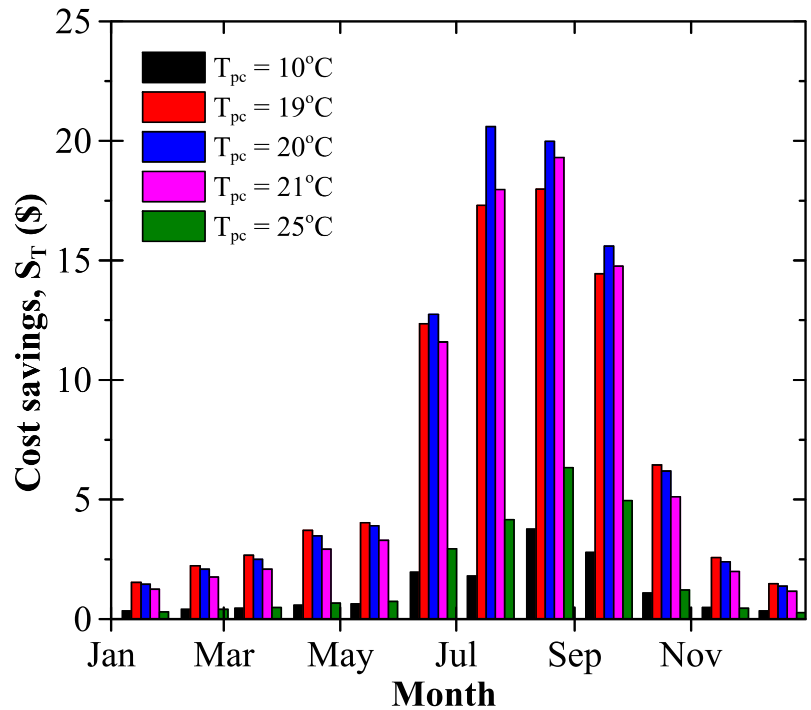


Effect of Phase Change Temp. in Los Angeles

- Parameters

$$T_{in} = 20^{\circ}\text{C},\ \Delta T_{pc} = 3^{\circ}\text{C},\ h_{sf} = 180\ \text{kJ/kg},\ \phi_c = 0.1,\ \phi_s = 0.08$$





- Optimum phase change temperature $T_{pc} \sim T_{in}$

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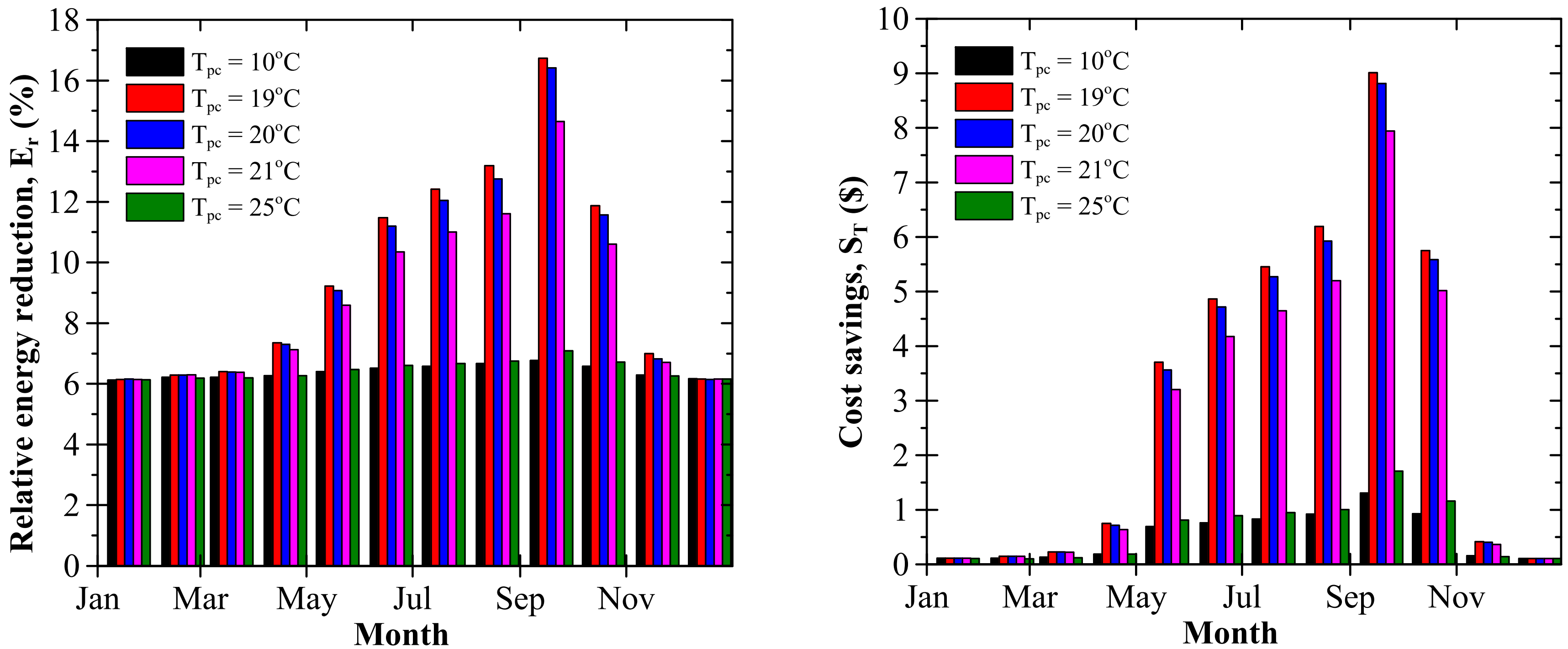
Effect of Phase Change Temp. in San Francisco

- Parameters

$T_{in} = 20^{\circ}C,\ \Delta T_{pc} = 3^{\circ}C,\ h_{sf} = 180\ kJ/kg,\ \phi_c = 0.1,\ \phi_s = 0.08$



- Optimum phase change temperature $T_{pc} \sim T_{in}$

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Summary

- Annual energy and cost savings maximized when phase change temperature is near the desired indoor temperature
- Microencapsulated PCM are most beneficial when the outdoor temperature oscillates around the desired indoor temperature
  - Better in Los Angeles than in San Francisco
- Adding microencapsulated PCM to the building envelop can significantly reduce the need for cooling in the hotter months in CA
- The effects of microencapsulated PCM on the energy needs for heating and the associated cost savings were small in CA
- Annual energy reduction and cost savings depend on wall orientation
  - Larger for the South- and West-facing walls in CA

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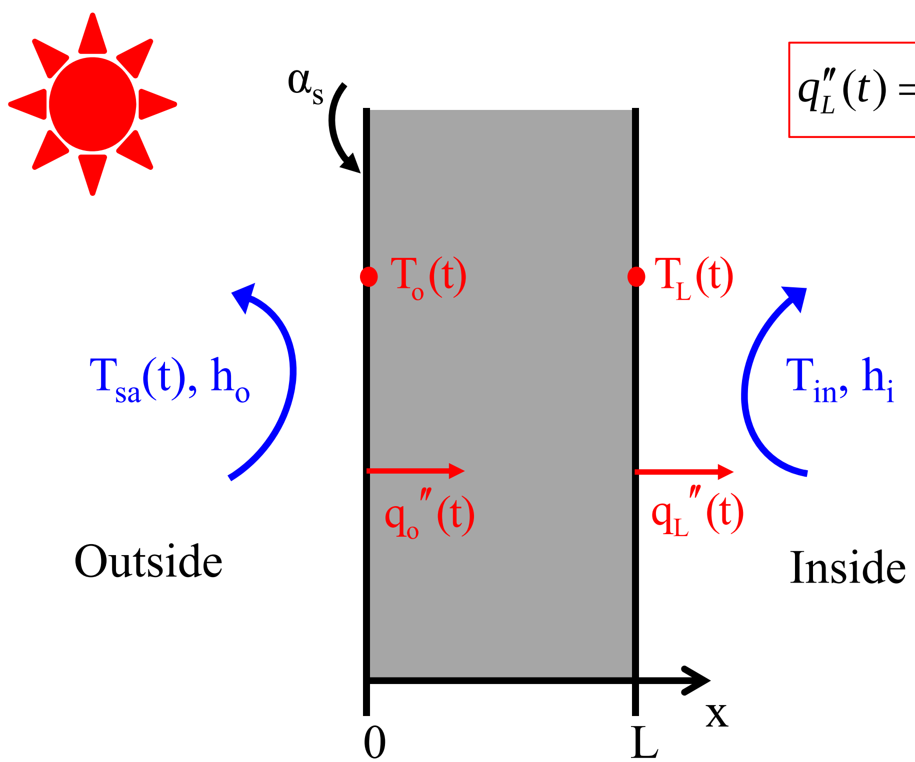
- Develop design rules and design tools for deployment

Modified admittance method for PCM
Figure of merit for PCM-composites

Admittance method

- The admittance method
  - developed as a computationally simple method to assess the transient thermal response of buildings to a sinusoidal sol-air temperature
  - The heat flux and temperature at the inner and outer wall surfaces can be related to the sol-air temperature via **decrement factors** and **time lags**[*,+]



$$\boxed{q_L''(t) = U\left[\bar{T}_\infty - T_{in} + f_{AM}\left(T_\infty(t - \phi_{AM}) - \bar{T}_\infty\right)\right]}$$

$$f_{AM} = \frac{q''_{L,\max} - q''_{L,\min}}{T_{sa,\max} - T_{sa,\min}} \cdot \frac{1}{U}$$

$$f_S = \frac{T_{L,max} - T_{L,min}}{T_{o,max} - T_{o,min}}$$

$$\phi_{AM} = t_{L,max} - t_{sa,min}$$

[*] N.O. Milbank and J. Harrington Lynn, Building Research Establishment vol. 74, issue 61, 1974
[+] L. Marletta et al., Energy and Buildings vol. 87, 2015

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Diurnal energy flux reduction predictions

- The admittance method was adapted to consider PCM melting to
  - Rapidly evaluate the thermal performance of a PCM-composite envelope
  - Reduce computational cost significantly
  - Simplify implementation in user-friendly design software

- Facilitate the design and evaluation of the energy benefits of PCM-composite in buildings
  - OPAQUE
    - http://www.energy-design-tools.aud.ucla.edu/opaque/request.php
  - HEED: Home Energy Efficient Design
    - http://www.energy-design-tools.aud.ucla.edu/heed/

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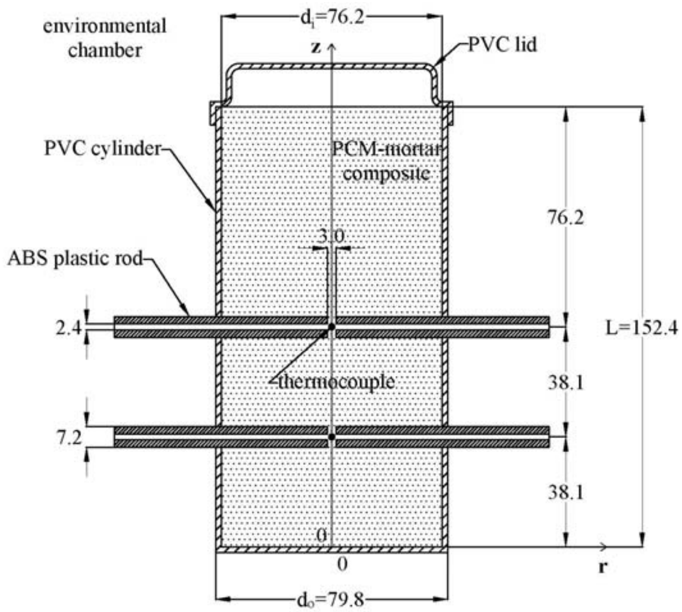
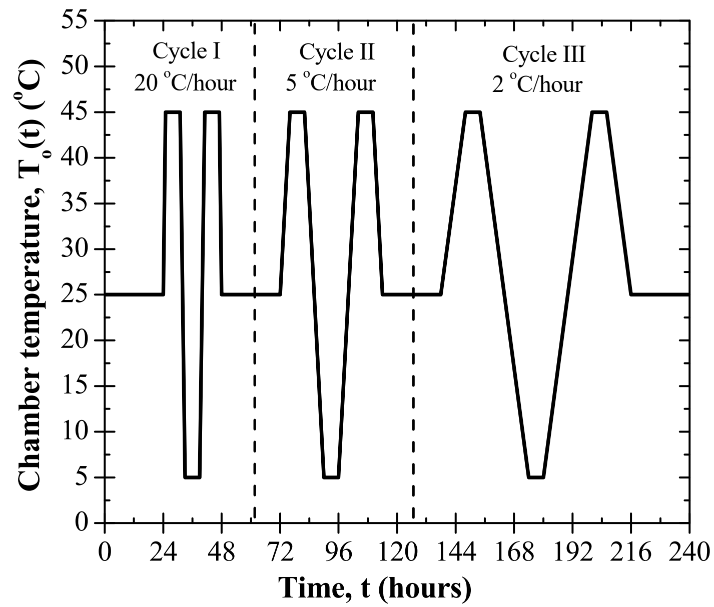
Figure of merit for PCM-mortar composites

- Specimens
  - Cylindrical mold: PVC canisters
  - Cement paste
  - Volume fraction of MPCM: 0-30%



- Sensors
  - Two thermocouples located along axis (r = 0)

- Procedure
  - Imposed successive heating and cooling ramps



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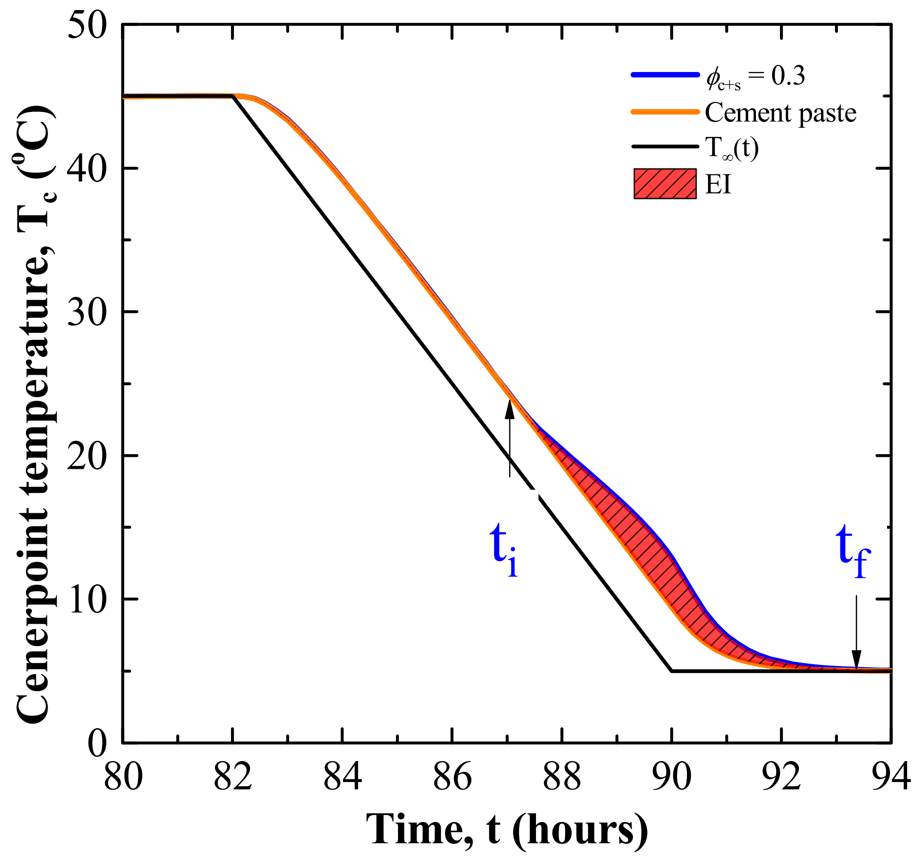
Energy indicator

- Energy indicator
  - Definition for heating or cooling

$$EI = \int_{t_i}^{t_f} |T_{PCM}(t) - T_{cement}(t)|dt$$

- Units
  - $^oC \cdot hr$

- Easily measurable
- Independent of heating and cooling rates



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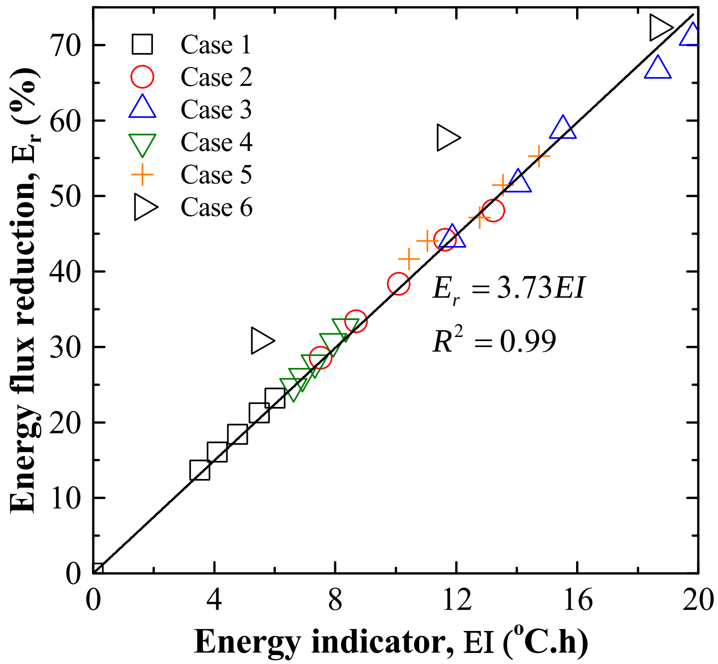
Correlation between EI and E_r

- Results
  - For a 4" thick concrete wall for different PCM volume fractions



- Conclusions
  - The energy indicator for a cylinder correlates with daily energy saving
  - Advantages of this FOM
    - accounts for combined effects of k_{eff}, $(\rho c_p)_{eff}$, h_{sf}, ϕ_{c+s}, dimensions
    - Test can be easily performed with a small amount of material

Conclusion

- Master material processing of concrete with MPCM
  - No aggregation, no breakage, durable
- Thermomechanical properties of PCM-mortar composites
  - Effective specific heat of PCM microcapsules and composites
  - Effective thermal conductivity
  - Effective compressive strength
  - Effective Young's modulus
  - Effective thermal deformation coefficient
- PCM-mortar composite building envelope
  - Reduce cooling needs in summer
  - Saving to ratepayers
  - Better in Los Angeles than in San Francisco
- Develop design tools and design rules for deployment
  - OPAQUE 3 software
  - Figure of merit for PCM composites

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Acknowledgement

- Students
  - Dr. Alexander Thiele*
  - Alex Ricklefs*
  - Amanda Fujii*
  - Gabriel Falzone
  - Zhenhua Wei
  - Benjamin Young
- Funding

STATE OF CALIFORNIA ENERGY COMMISSION

* Graduate students who graduated and are now working in CA

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Thermomechanical Properties of PCM-Mortar Composites

- Specific heat of PCM microcapsules
  - Numerical modeling
    - A.M. Thiele, G. Sant, and L. Pilon, 2015. Diurnal Thermal Analysis of Microencapsulated PCM-Concrete Composite Walls. *Energy Conversion and Management*, 93, 215-227.
  - Experiments
    - A.M. Thiele, Z. Wei, G. Falzone, B.A. Young, N. Neithalath, G. Sant, and L. Pilon, 2016. Figure of Merit for the Thermal Performance of Cementitious Composites containing Phase Change Materials. *Cement and Concrete Composites*, 65, 214-226.
- Thermal conductivity of PCM-mortar composites
  - Numerical modeling
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  - Experiments
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